Transmutation Options

Advanced Fuel Cycle Initiative
Semi-Annual Review Meeting
August 28, 2003

Robert N. Hill
Nuclear Engineering Division

Argonne National Laboratory

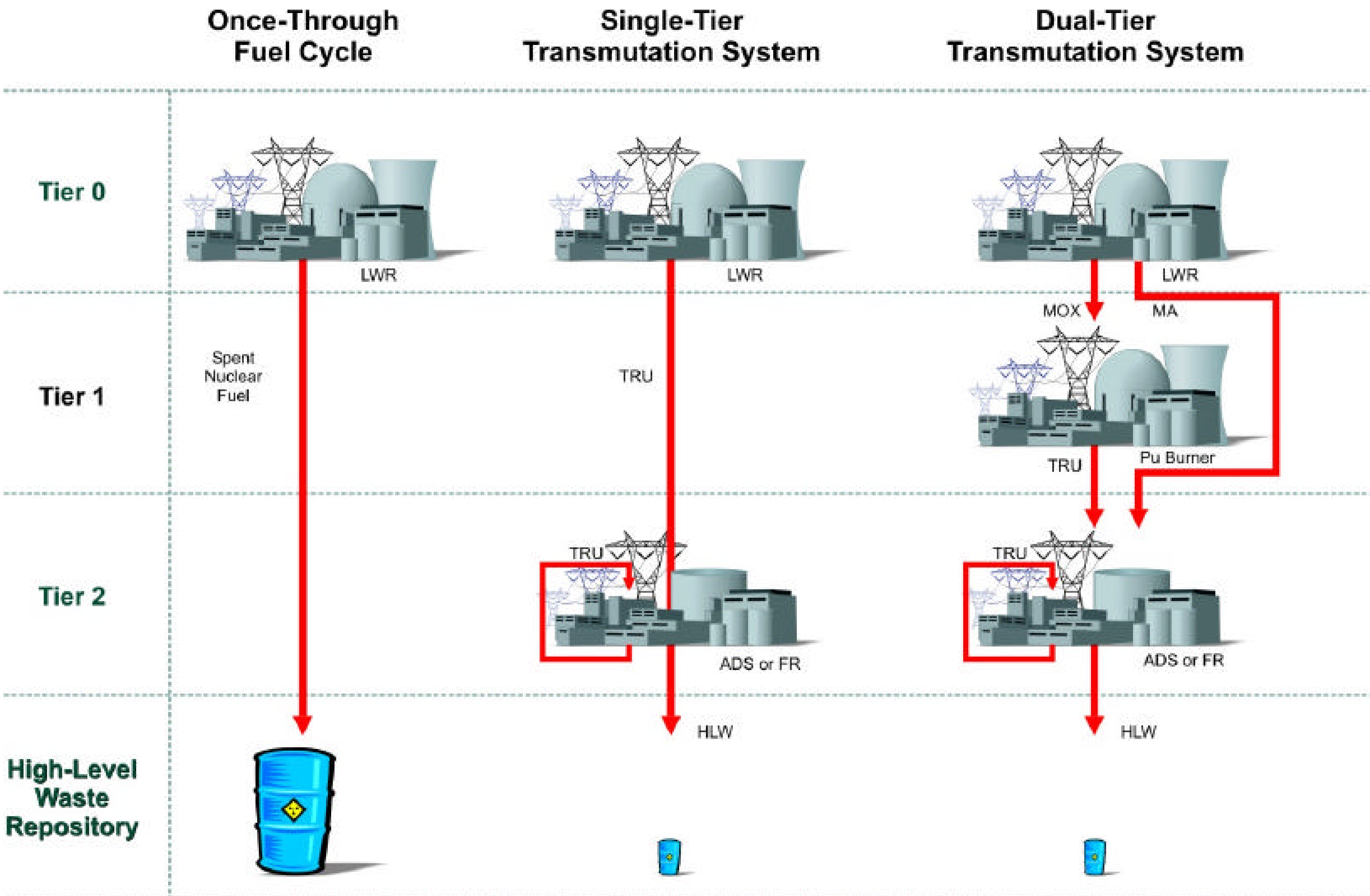
Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Transmutation Options Objectives

- **<u>Systematic</u> assessment of transmutation system technology and implementation options**
  - Diverse body of existing international work on transmutation
  - Most research focused on details of specific options
  - Identify promising options and technology gaps
- **Synthesis of previous transmutation activities**
  - Overview provides added insights
  - International work may have impact on AFCI approach (e.g., maturity of LWR nonfertile fuel research)
- **Respond to inquiries regarding transmutation strategy**
  - Integrate work to respond to NERAC and external questions
  - Address key systems planning/direction issues

Transmutation System Approach



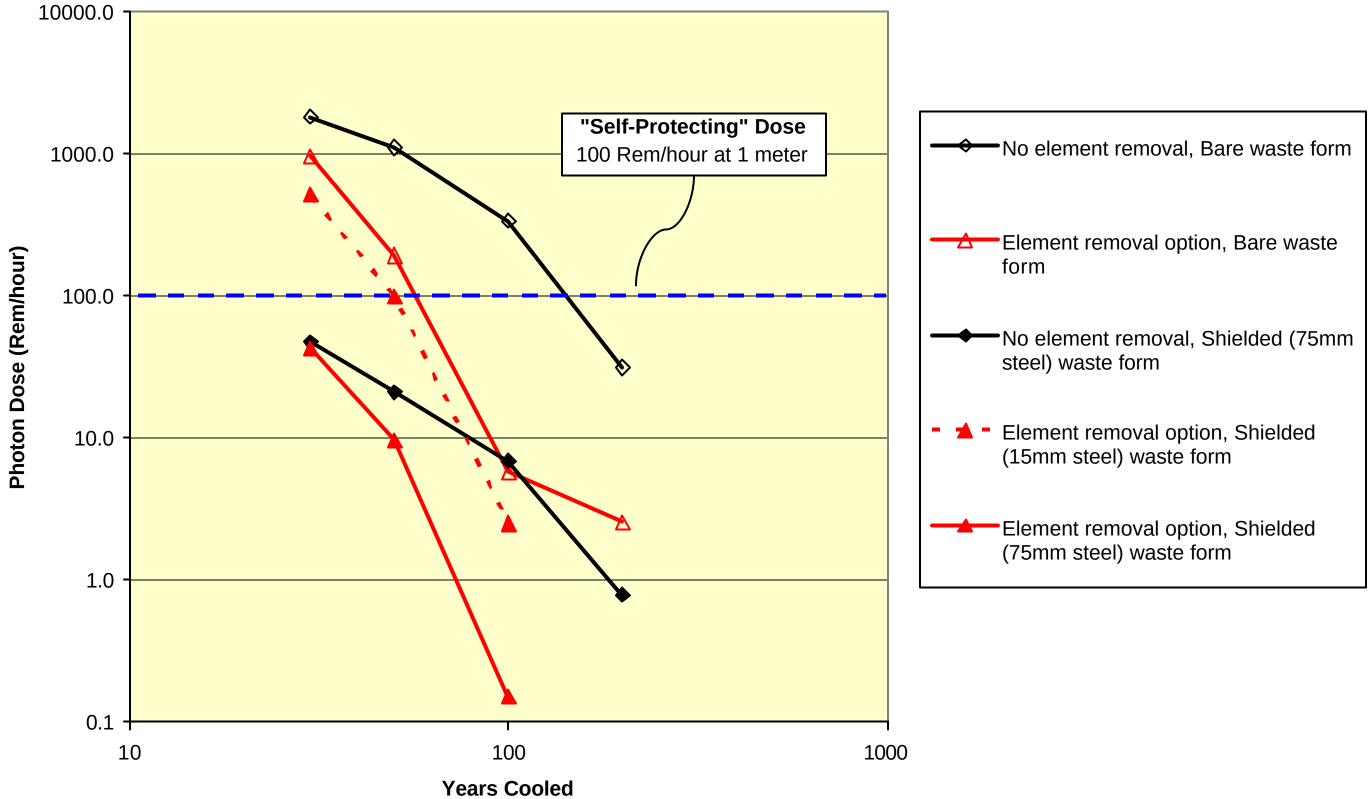
Recent Highlights of Transmutation Options Studies

- **Assess characteristics of interim waste forms**
  - Impact of partial separations with and without transmutation
  - Evaluation requested by ANTT Subcommittee
- **Systematic evaluation of PWR transmutation strategies**
  - Review of extensive international studies
  - Comparison of multi-recycle options
  - Homogeneous and heterogeneous (target) schemes compared
- **Systematic evaluation of FR transmutation strategies**
  - Compare transmutation potential of Gen-IV fast spectrum concepts
  - Development and safety evaluation of low conversion ratio FR

Interim Storage Evaluation

- **LWR spent fuel is processed to remove key elements**
  - Uranium removed for mass reduction
  - Cesium and strontium removed to simplify handling
  - Transuranics (TRU) and other fission products remain
- **Characteristics of interim storage form analyzed**
  - Benefit of direct disposal to repository would be limited
    - *Long-term heat load is retained*
  - Self-generated radiation dose was estimated
    - *For 21 PWR assemblies (single YM waste package)*
    - *Storage form is self-protecting for ~50 years (next viewgraph)*
  - In a similar manner, criticality and thermal management issues were considered
    - *Waste can be safely handled and pacakaged*

Dose Evaluation of Interim Storage Package



- **Photon dose is greater than 100 rem/hr for ~50 years**
  - Key contributor is Eu-154 with 8.6 yr half-life and high energy
  - Impact of thin steel wall on dose rate is minor
  - Neutron dose is much smaller (order of 1 rem/hr)

Transmutation by Recycle in PWRs: Collaborative Assessment with CEA

First, the physics of LWR multi-recycle was assessed

- **Transmutation character varies with the moderator-to-fuel ratio**
  - Capture/fission ratio higher at thermal energies
- **Impact of extended burnup was considered (next viewgraph)**
  - Plutonium quantity per unit energy decreases
  - Plutonium quality degrades with burnup
  - More higher actinides are generated at higher burnup
- **Utilization of MOX fuel exacerbates both plutonium vector degradation and higher actinide generation**
- **Impact of repeated recycle evaluated for range of moderator-to-fuel ratios**
  - Hard spectrum and degraded vector increase enrichment
  - Can have adverse affect on reactivity coefficients
    - *Positive void effect may limit the allowable MOX enrichment*

Plutonium and Minor Actinide Production

BURN-UP (GWd/t)	Initial Enrichment	TOTAL Pu	Np 237	Am 241	Am 243	Cm 244	Cm 245
		kg/MTIHM					
42	3.70 %	**11.7**	0.62	0.20	0.17	0.05	0.00
55	4.50 %	**12.6**	0.76	0.21	0.25	0.10	0.02
65	4.95 %	**13.3**	1.01	0.25	0.38	0.18	0.02
		kg/TWeh					
42	3.70 %	**34**	1.81	0.58	0.49	0.14	0.01
55	4.50 %	**28**	1.70	0.47	0.56	0.22	0.02
65	4.95 %	**25**	1.90	0.48	0.71	0.34	0.03
65	6 % - ***MOX***	**-70**	0.5	8.6	5.7	3.3	0.7

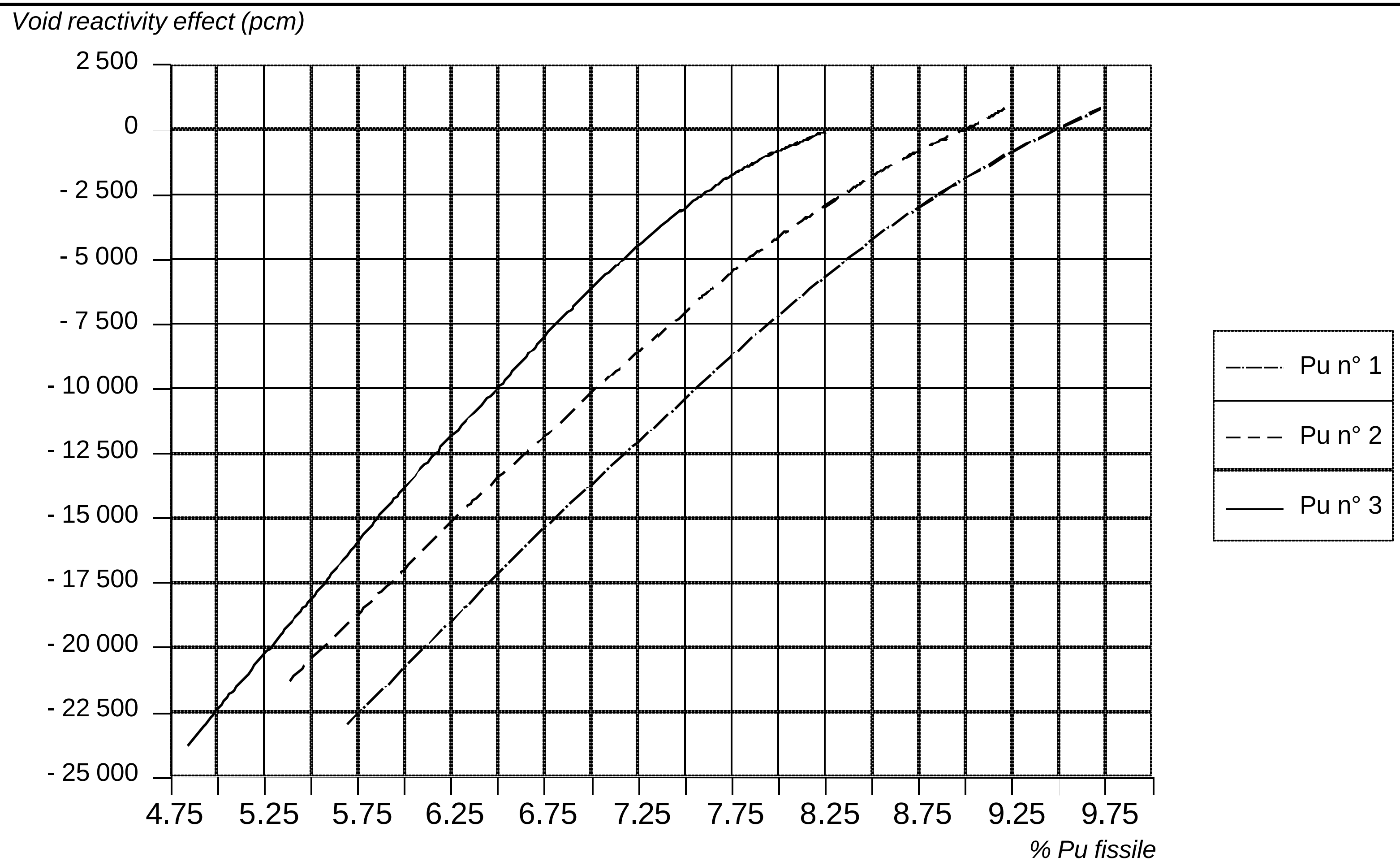
- **Plutonium quantity for given HM loading increases with burnup**
- **Per unit energy, plutonium quantity decreases**
  - Thus, for given power production, less plutonium generated
- **However, more minor actinides generated at higher burnup**
- **MOX loading results in net destruction of plutonium**
  - But, minor actinide production rate is greatly increased

Degradation of Plutonium Vector with Recycle

Reycle #	1	2	3	4	5	6
^{238}Pu	0.11	1.17	1.85	2.55	2.74	5.63
^{239}Pu	79.9	67.9	58.1	54.3	42.5	33.9
^{240}Pu	17.3	18.6	22.6	23.2	29.2	29.1
^{241}Pu	1.45	9.11	10.8	11.7	14.3	13.7
^{242}Pu	0.50	2.69	5.60	7.14	9.82	16.2
^{241}Am	0.57	0.55	1.20	1.18	1.44	1.39
Fissile %	81.4	77.0	68.8	66.0	56.8	47.7
MOX Enrichment Requirements						
Self MOX Recycle	6.0	7.6	8.6			
Recycle w/dilution	6.0	6.6	7.0			

- **Plutonium vector degrades each recycle**
  - Fissile fraction decreases, requiring higher MOX enrichment
- **Enrichment increases from 6% (first MOX recycle) to 8.6% (after two MOX recycles)**
  - Can limit to 7% by dilution with plutonium from UOX assemblies

Impact of MOX Enrichment on Void Effect

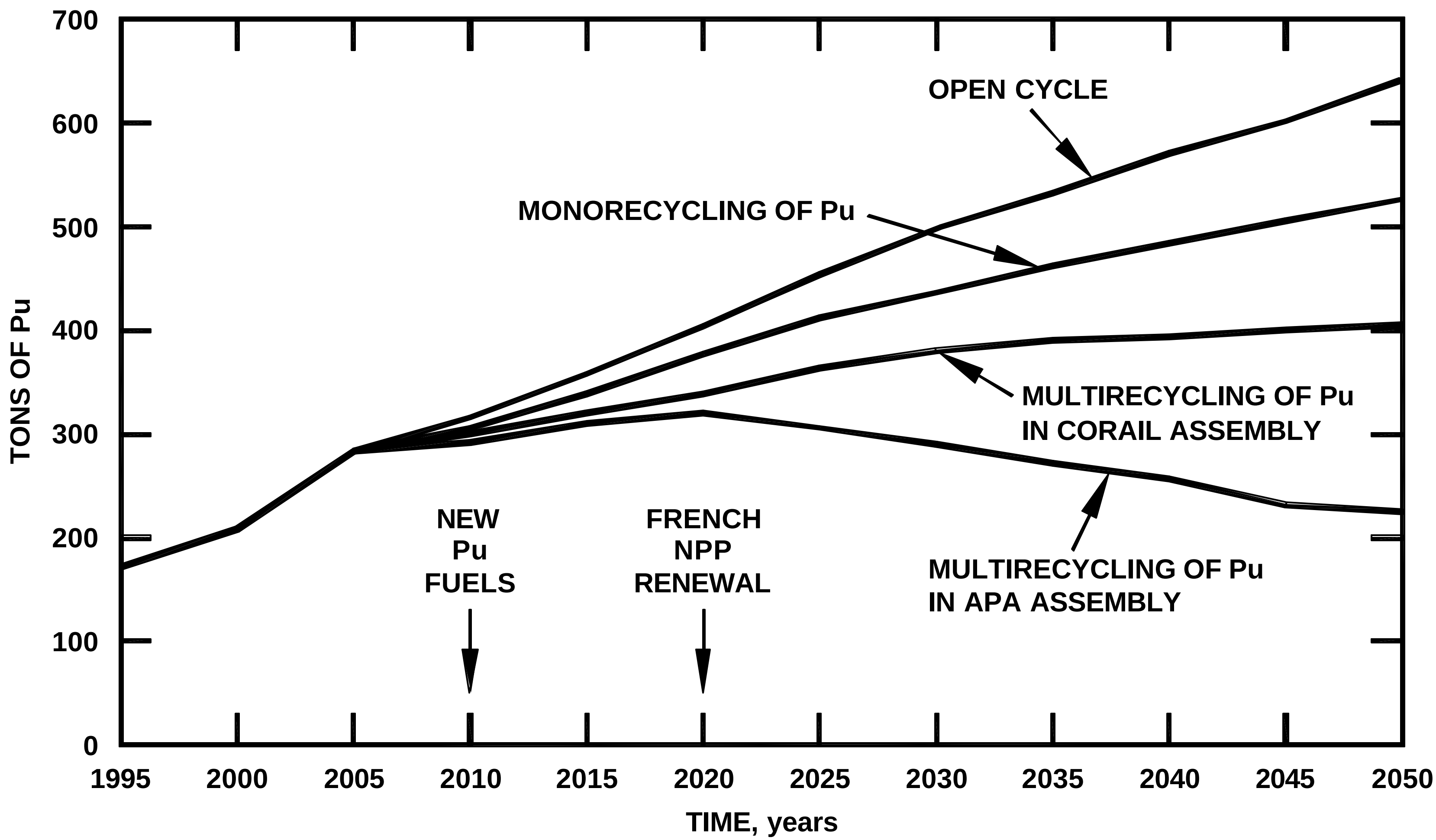


- **Degraded vector also hardens the LWR spectrum**
- **Zero void enrichment limit decreases from 9.5 to 8.25%**

Multi-Recycle Strategies for PWRs

- **Enriched uranium support (i.e., only partial loading of Pu-based fuel) mitigates penalties and allows plutonium multi-recycle**
- **Practical implementation of plutonium and/or minor actinide (MA) recycling has been explored**
  - Pu+MA mixed with enriched uranium (MIX concept)
  - Separate MOX and enriched uranium pins (CORAIL concept)
  - Pu+MA loaded in nonfertile fuel
    - *Can achieve greater net destruction rate*
- **Selective recycle of TRU elements considered**
  - Curium removal prevents higher actinide build-up
    - *However, difficult to separate and store curium*
- **Limited recycle of TRU may be preferred**
  - With remaining materials consumed in a complementary transmuter

Pu Management Options (French Case)



Thermal Reactor Strategies

Several other items regarding transmutation in LWR systems need to be addressed:

- **Assessment of BWR transmutation studies**
- **Review of transmutation studies for reduced moderation water reactor (RMWR) - *ongoing***
- **Potential for transmutation in VHTR is a key issue for congruence with Generation-IV program**
- **Deep burnup options in thermal (gas or LWR) systems may reduce the reprocessing requirements**
  - Fuel forms to tolerate burnup must be developed
  - Larger reactivity variations must be managed
    - *Burnable poisons*
    - *Refined loading strategies*

Low Conversion Ratio Fast Reactor

- **Ratio of transuranic (TRU) production to destruction ratio is defined as the conversion ratio (CR)**
- **Results of previous fast burner reactor studies**
  - If limited to conventional fuel enrichment, the minimum conversion ratio that can be achieved is ~0.5
  - At non-uranium limit, adverse impacts were observed
    - *High reactivity loss rates*
    - *No Doppler coefficient*
- **Low conversion ratio fast reactor design study was conducted in FY02 to explore range of CR from 0.5 to 0.0**
  - Favorable passive safety behavior retained at low CR
- **This year, low conversion ratio system point design specified**
  - CR~0.25 chosen for 50% fuel enrichment
  - Compact configuration developed
  - Detailed safety assessment is being conducted

Transmutation Performance of Fast Transmuter Options

System	Conventional Burner	Low CR Burner	ADS
TRU Conversion Ratio	0.55	0.25	0.00
Net TRU consumption rate (kg/yr)	108	193	270
Transmuter Diameter (cm)	338	186	208
Transmuter Height (cm)	46	113	113
Fuel Volume Fraction,	0.38	0.22	0.19
Fuel Enrichment, % TRU/HM	27/33	44/56	100
TRU Inventory, MT of TRU	4.36	2.25	2.66

- **TRU consumption rate significantly higher for low conversion ratio systems**
  - Non-uranium limit of 270 kg/yr for 840 MWt size system
  - Achieve 75% this rate at CR=0.25
- **Enrichment is roughly 50% for low conversion ratio burner**
- **Compact configuration can be employed with reduced fuel volume fraction**
  - Economic benefit for 1.5 meter reduction in system diameter
  - TRU inventory is roughly ½ that of high leakage burner

Safety Parameters of Fast Transmuter Options

System	Conventional Burner	Low CR Burner	ADS
TRU Conversion Ratio	0.55	0.25	0.00
Net TRU consumption rate (kg/yr)	108	193	270
Fuel Enrichment, % TRU/HM	27/33	44/56	100
Burnup Swing (%Δk)	1.35	4.26	4.14
Delayed Neutron Fraction	0.0032	0.0028	0.0023
Sodium Void Worth ($)	3.36	4.85	-0.7
Radial Expansion Worth (cents/C)	-0.34	-0.35	-0.42
Doppler Worth (cents/C)	-0.066	-0.052	0

- **Burnup reactivity loss rate much faster at low conversion ratio**
  - Must account for reactivity compensation (e.g., shorter cycles, more CRs)
- **Void worth ~$1.5 higher for compact configuration**
  - Expansion coefficients are roughly conserved
- **Doppler coefficient decreases with conversion ratio**
  - Still significant at 50% enrichment, but zero with nonuranium fuel
- **Passive safety performance is being analyzed in detail**

Fast Reactor Strategies

Several other items regarding transmutation in fast spectrum systems need to be addressed:

- **Comparison of transmutation performance of the fast reactor systems proposed in Generation-IV**
  - Collaborative study with CEA initiated to evaluate potential
    - *Sodium, gas, and lead-cooled FRs compared*
  - Transmuter designs need to be developed in more detail
- **For double tier transmutation system, transmuter performance will depend intimately on first tier performance**
  - Low fissile content leads to high enrichments
  - Fuel handling may be severely complicated by deep burnup in thermal spectrum system (higher actinide generation)
- **Relative performance of reactor and ADS transmuters**
  - Preferred system may depend on growth scenario